MICRO VALVING FOR SPACE APPLICATIONS

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ABSTRACT

We report on the development of silicon micro valves for micro-propulsion and other space applications here at JPL. The devices are required to have an extremely low mass, low power consumption rate, low leak rate, long shelf life, as well as immunity to particulates, corrosive fuels, and the perils of space launch and travel. Also, it should be easy to integrate with other micro fluidic systems being developed by JPL and NASA. Currently, no commercial valve meets all these requirements. The JPL micro valve attempts to address the unique problem of space. To date, a preliminary design has been developed, the fluidic path prototyped, and operation as a regulator has been demonstrated. This paper contains the justification for the design, the results of initial testing, and the proposed plan to realize a stand alone silicon micro valve suitable for space applications.

INTRODUCTION

Micro ElectroMechanical Systems (MEMS) have always had huge potential applications for space. Any reduction in mass or power required for a space instrument or subsystem results in an exponential savings for launch cost as well as a significant increase in mission lifetime. It is a cry for MEMS if ever there was one. Unfortunately, no NASA project engineer will embrace a smaller subsystem if it means a sacrifice of performance, and certain aspects of MEMS have yet to rise to the occasion.

MEMS fluidics and sensors have come a long way. Unfortunately, MEMS control actuators have not kept up. For example, very complicated yet precise analysis for life can be done on a silicon chip. However, we have yet to find a silicon valve that can keep the chamber sealed and the reagents from subliming away during the journey to Mars. We can implement the entire propulsion system for a small spacecraft in silicon, yet have no way of controlling the flow of the propellants. Indeed, NASA has identified a low-leak space qualified regulator valve as a key technology for enabling micro-instruments and micro-spacecraft, the future of space exploration.

Recently, Juergen Mueller of JPL's Advanced Propulsion Technology Group conducted a survey of the state-of-the-art valving possibilities for micro spacecraft [1]. He lists several requirements for candidate devices, which are summarized in table 1. While commercial MEMS valves are generally well within the power and weight requirements, they often fall short of the leak rate or operational temperature specifications.

Therefore, JPL has undertaken the task of developing a micro valve and fluidic regulator suitable for micro propulsion and other space applications. We have borrowed the best from typical MEMS valve designs, especially in the general structure of the device. However, we have implemented certain modifications that we believe will lead to a superior valve. These include the choice of actuator, careful attention to sealing surfaces, and the implementation of a filter.

Currently, we have a preliminary design, and prototypes of the fluidic path in the valve, including a filter. These structures have been tested, and function

Table 1: Valve Requirements for NASA deep Space Miniature Spacecraft Propulsion

| PARAMETER	VALUE
Leak Rate	< 0.3 scc/hr Helium
Actuation Speed	< 10 milliseconds
Inlet Pressure (liquid)	0 – 300 psia
Inlet Pressure (gas)	0 – 3000 psia
Power Consumption	1 W, 5 V
Weight	< 10 gm
Temperature	-120 °C to 200 °C
Particulates	< 5.0 micron

as a fluidic regulator has been shown. Surprisingly, packaging and testing have proven to be just as challenging as the design itself. In the future, we intend to integrate and test the actuator with the fluid path, build comprehensive analytical models of the device capable of predicting the performance of future designs, and experiment with different seat materials in order to develop the most robust sealing surface possible.

DESIGN

Larger, commercially available diaphragm valves inspire the design of this valve [2]. The stand-alone device has a square footprint of 1.6 cm on a side, and should have a height of less than six millimeters. This may seem large for a MEMS device. However, since a valve's leak rate is mostly dependent on its sealing area, we feel that it makes sense to build a larger than typical micro-valve to satisfy the requirements for space applications.

The valve begins as three separate parts: the seat, the diaphragm, and the actuator, as shown in figure 1. The base of the valve is known as the seat. This is the part that will interface with the rest of the micro-fluidic system. The seat contains the inlet and the outlet, as well as a set of seal rings around each opening inside the device. The center section of the valve is known as the diaphragm wafer. It has a circular corrugated diaphragm, with a circular boss in the center, covering both openings in the seat. The boss is either fully suspended by the diaphragm, or is also supported by four silicon suspensions. Finally, the actuator consists of a piezoelectric disk in a rigid housing. All three parts are bonded together using a metal-to-metal diffusion bond.

Operation Cross sections of the device are shown in figures 2a and 2b. The valve is normally closed. The piezoelectric stack is forced into a slightly contracted position during the bonding process, to apply a large
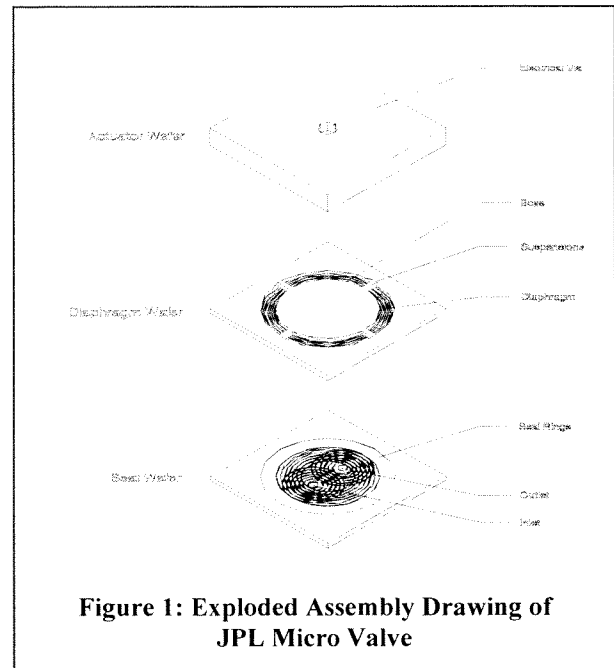

Figure 1: Exploded Assembly Drawing of JPL Micro Valve

sealing force on the two openings. A simple Young's Modulus calculation can be used to determine the initial sealing force. Application of a voltage across the stack will cause it to contract even further, lifting the diaphragm away from the seat, as shown in figure 2b (not to scale). This creates a channel between the two openings, allowing for the passage of fluids. Because of the diaphragm, dead space is minimal.

Actuator. While this may seem like any typical MEMS valves [3,4], several design innovations have been implemented to try and satisfy the requirements for space applications. The most crucial of these criteria is a low leak rate. The force density of the actuator has perhaps the largest influence on leaks and reliability in a valve. The harder to surfaces are pressed together, the less fluid will pass through. Also, a large sealing for may be capable of embedding or crushing any particulates that could damage the integrity of the
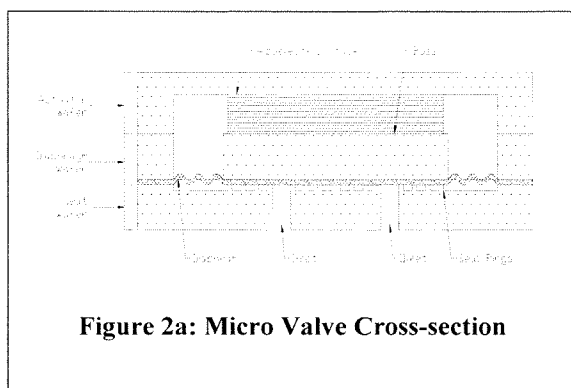
Figure 2a: Micro Valve Cross-section
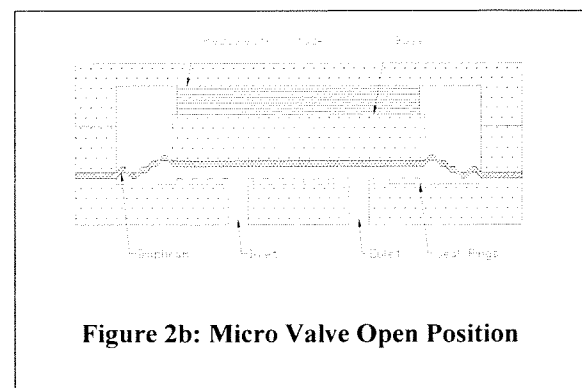
Figure 2b: Micro Valve Open Position

sealing surface.

Table 2 is a comparison of various actuation schemes that are amenable to micro-machining processes and have been previously utilized in MEMS valves. These include thermo-pneumatic, bimetallic, shape-memory alloy, electrostatic, and piezoelectric. The equations used are back of the envelope calculations intended to provide an order of magnitude on the forces generated [5-9]. The actual force can be significantly influenced by the specific actuator design. They are sized for one of the prototyped fluidic channel, where the sealing boss is a 1 cm diameter disk, suspended on a 1.4 cm diameter membrane.

The shape memory alloy and piezo disks seem to be the clear winners for force density. Unfortunately, the actuation time for the Flexinol ™ shape memory alloy used for this example would be on the order of minutes for this size actuator. Therefore, the piezo disk is our choice for actuation of this valve. Unfortunately,

piezoelectric disks do have their challenges. Displacements are very small, and required voltages are very high. The latter will be overcome with the use of laminated piezoelectric materials and interlaced electrodes. The former may be overcome with the used of cantilever or bi-morph schemes. However, for many space applications, a simple piezo stack with its large force density and limited deflection seems to be the better option.

Seat Design. The seat also displays some unique qualities that should improve the valve's performance and reliability. The first is the larger sealing area between the inlet and the outlet. Second, we apply force to both the inlet and the outlet of the valve. Finally, there is a large sealing area around both openings, preventing leakage to the environment. This seal is implemented through metal-to-metal diffusion bonding, a versatile low temperature process that typically yields better seals, capable of lower leak rates

Table 2: Comparison of Typical MEMS Valve Actuation Schemes

	thermo-pneumatic	bi-metalic	shape-memory alloy	electrostatic (w/ spring)	piezo electric
Governing Equations for Sealing Force	$F = A\ P_2\ (T_1 / T_2)$ P = pressure A = area T = temperature	$F = w\ t^3\ (\Sigma E)\ d / l^3$ w = beam width t = beam thickness ΣE = sum of moduli l = beam length d = deflection	$F = K\ A\ \delta$ A = actuator area δ = strain K = constant, based on Flexinol ™ data	$F = \varepsilon_0 A V^2 / 2g^2$ g = gap, V = voltage, A = area	$F = E_P\ A\ \delta$ E_P = piezo modulus A = area, δ = strain
Assumptions	Ideal Gas, 100 K Δ Temp, No Heat Loss, No Δ Volume	Ni–Si Bi-metallic, Max stress < Yield	Manufacturer's data for Flexinol ™ wire, 4% strain	gap > 3×deflect, V < air breakdown,	0.1% strain, V = maximum
Constants		E_{Si} = 190 GPa E_{Ni} = 200 Gpa Y_{Si} = 7 Gpa Yni = 80 MPa	K = 0.18 GPa	ε_0 = 8e-12 F/m V = 1.2 V	E_P = 63 GPa
Actuator Geometery	Gas Capsule 10 mm diameter 5 mm high	8 2mm × 2 mm Beams 100 μm thick, (50/50 Ni, Si)	SMA disk 10 mm diameter 5 mm high	Capacitor disk 10 mm diameter w/ spring	Piezo disk 10 mm diameter 5 mm high
Force	~ 1 N	~ 2 mN	~14 kN	~ 2 μN	~ 5 kN
Max Deflection	-	10 μm	20 μm	5 μm	5 μm
Power	high	high	high	low	low
Actuation time	long	long	long	short	short

than many of the traditional techniques such as epoxy bonds typically seen in MEMS.

Immunity to particulates will be realized through the unique geometry of the sealing area. Instead of a flat sealing surface, we have implemented a series of closely spaced 20 µm high rings, expanding outward from both the inlet and the outlet. Because these rings are so many and so dense, they still provide a large sealing area. However, this configuration has the added benefit are being able to withstand small particles that may be in the flow. Most particles will be trapped in the valleys between the rings. Any single scratch that may occur will likely not create an open path from the inlet to the outlet, since it will only affect a limited number of rings. . These rings may be very narrow to provide knife-edge seals, or very wide to increase the total sealing area, depending on the design criteria.

Some particles, however, may settle on the sealing surface. Therefore, the material choices for that surface are still vital. We must explore soft materials such as teflon, which allow for offending contaminants to

Figure 4: SEMs of Seat Wafer
a) Inlet and outlet
b) Close up on seat
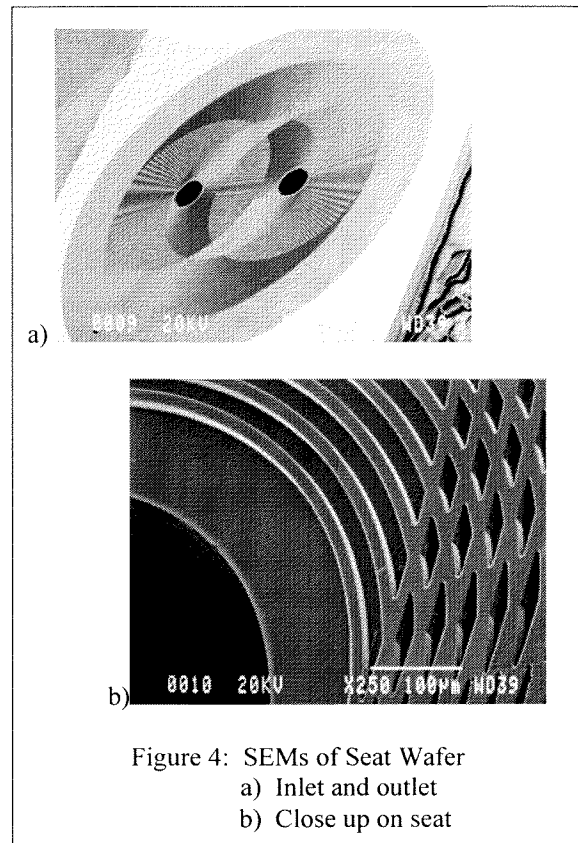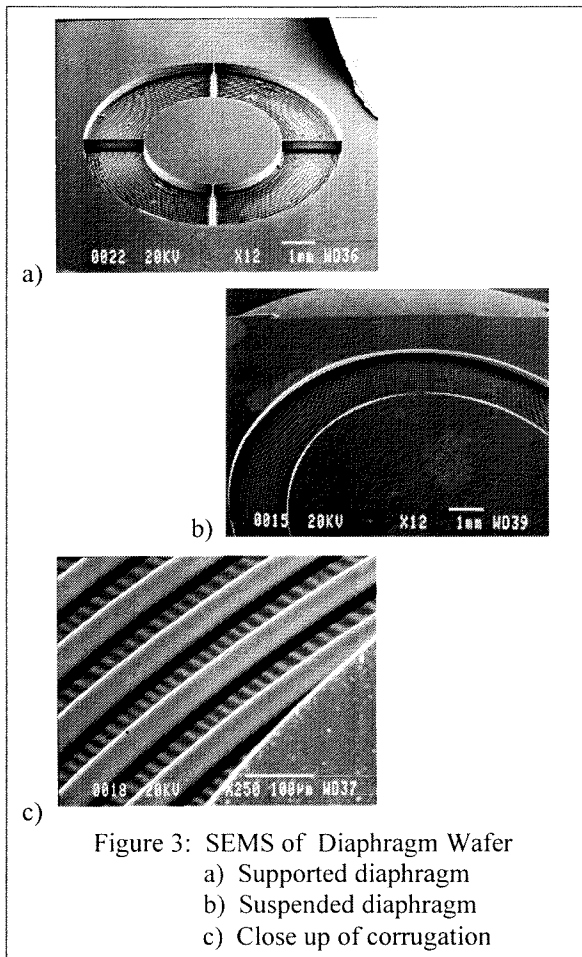
become embedded into the seat without creating a leak. Also, we must investigate hard materials such as silicon nitride or titanium nitride that can crush the same particles with the same end effect. Materials will be studied not only for their physical properties, but also for their chemical inertness in the face of typical propulsion fuels, as well as possible integration into a batch fabricaiton process. This kind of materials research is of vital importance to the success of micro valves in general. Yet very little has been done in the area.

FABRICATION

Figures 3 and 4 shows some examples of finished parts for the JPL micro-valve. The dimensions of both the diaphragm and seat are 16 mm by 16mm by 0.4 mm. The fabrication process relies heavily on a Deep-Trench Reactive Ion Etch (DRIE) to machine circular features into silicon [10]. Presently, only seats and diaphragms have been fabricated and assembled. We feel it necessary to thoroughly test the seat-diaphragm structures before embarking on the design and implementation of the actuator.

Both pieces are bulk micro-machined from n-type <100> silicon wafers. In order to create circular shapes, we use a novel DRIE technique. This involves a

Figure 3: SEMS of Diaphragm Wafer
a) Supported diaphragm
b) Suspended diaphragm
c) Close up of corrugation

series of alternating etching / passivation steps to achieve straight side-walls in silicon irrespective of the crystal plane. The etching is done by a combination of SF_6 and O_2 gasses, and the passivation by a combination of C_4F_8 and O_2 gasses.

We also use a low-pressure chemical vapor deposition (LPCVD) system to passivate the surfaces and fabricate the diaphragm. Finally, we use metal-to-metal diffusion bonding technique to assemble the parts. Bonding surfaces are metalized with a Ti/Pt/Au layer, and then held under high temperature and pressure to create a single diffused layer, thereby bonding the two pieces

The process for fabricating the seat-diaphragm assembly is outlined below.

1) First, seal rings and corrugations are etched into the seat and diaphragm wafers, respectively.
2) Patterning and DRIE etching through from the backside to fabricate the inlet and the outlet.
3) A low-stress 1um thick silicon nitride membrane is grown over all surfaces of both wafers.
4) Boss is released using DRIE etching from top of diaphragm wafer.
5) Next, metal is evaporated onto the bonding

Table 3: Experimental Data on Micro-Valve

surfaces and patterned to create bonding areas.
6) The backside of the diaphragm wafer is patterned an etched to release the boss.
7) The wafers are bonded.

For the actuator, we intend to use a silicon housing with a piezoelectric disk. Metalized vias will be etched through the housing to make electrical contacts. This piece will also be bonded to the seat-diaphragm assembly through a metal-to-metal diffusion process.
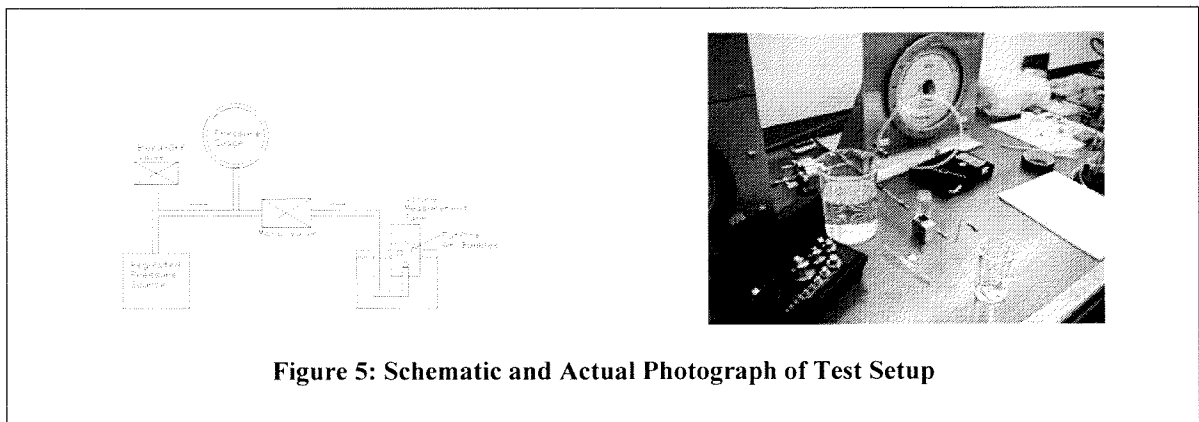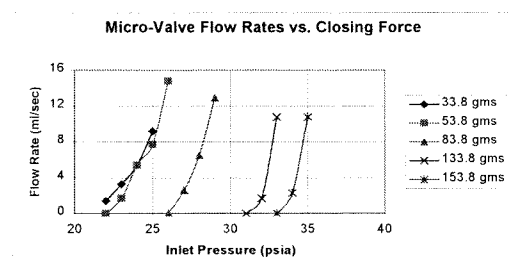
TESTING

As stated above, the prototyped fluidic channels have been tested and operation as a regulator has been verified. While this seems relatively straightforward, mating MEMS systems to testing apparatus has unexpectedly proven to be one of the larger challenges to this project. Traditional methods of plumbing gasses to a valve and measuring flows are too bulky to work here. New couplings and measurement techniques needed to be developed to interface the micro and macro worlds.

Figure 5 shows the preliminary testing apparatus. The valve is mounted onto a metal plate from which the inlet and outlet holes could easily be accessed. Air pressure at the inlet can be accurately varied using a series of gauges and regulators. The total volume of flow can be measured at the output. This and a precision timer are used to determine flow rate. Preliminary tests include measuring the open flow rate vs. inlet pressure, and the force necessary to stop flow verses inlet pressure.

Typical results are shown in table 3. The greater the sealing force, the larger the inlet pressure required to achieve the same flow rate. This shows that this configuration does indeed operate as a regulator. The next step with this apparatus will be to use a

Figure 5: Schematic and Actual Photograph of Test Setup

piezoelectric stack to apply sealing force. This would be a closer approximation to the final form of the valve with an integrated actuator.

We must also improve the flow rate measurement scheme. As it is now, the test station is not sensitive enough to determine the leak rates for given inlet pressures and maximum sealing forces. For such measurements, we will most likely have to test the device under vacuum with a mass spectrometer.

CONCLUSIONS

Micro and miniature fluidic systems have a broad range of applications both in research and in industry. NASA has a keen interest in reducing the size and mass of its fluidic systems, both in science instruments and in spacecraft subsystems such as propulsion. Quality MEMS valves will be vital to micro-fluidics. They are also the most difficult problem to solve.

The space environment is very unique, as are the kinds of tasks that people actually wish to accomplish in space. Mass is at a premium, and cost efficiency takes a back seat to performance. MEMS is tailor-made for the space industry. At JPL, we are attempting to blend simple innovations with proven configurations in order to produce the best possible valve for space applications.

ACKNOWLEGDEMENTS

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